

NPS ARCHIVE
1964
SYCK, J.

**THERMAL CONVECTION IN LAKE WASHINGTON,
WINTER 1962-1963**

JAMES MARVIN SYCK

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93942-5101

Library
U. S. Naval Postgraduate School
Monterey, California

1

THERMAL CONVECTION IN LAKE WASHINGTON,

WINTER 1962-1963

by

JAMES MARVIN SYCK

A thesis submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

UNIVERSITY OF WASHINGTON

1964

Approved by _____

Department in which degree is granted _____

Date _____

DEPARTMENT OF THE NAVY

COMMANDING OFFICER
NAVAL R. O. T. C. UNIT
UNIVERSITY OF WASHINGTON
SEATTLE 5, WASHINGTON

NPS Archive

1964

Syck, J.

(

~~5/15~~

C

ACKNOWLEDGMENTS

The author wishes to thank the members of the faculty of the Department of Oceanography for their assistance in this work. Particular thanks to Dr. Clifford A. Barnes for pointing out the possibilities of using Lake Washington for studying convective flows. Thanks also are given to Drs. Maurice Rattray, Jr. and T. Saunders English for their many helpful suggestions in the preparation of the manuscript.

Incoming solar radiation data was obtained from the Department of Atmospheric Sciences at the University of Washington.

This research was performed while the author was on active duty with the United States Navy in the Junior Line Officers Advanced Scientific Program administered by the Bureau of Naval Personnel. Financial support of the field work came in part from Navy contracts Nonr-477(10) and Nonr-477(37).



TABLE OF CONTENTS

INTRODUCTION	1
Purpose	1
Nature of the Problem	1
Previous Work	1
Description of Lake Washington	3
Materials and Methods	4
INVESTIGATION	6
The Temperature Structure	6
Heat Budget	8
Downslope Current off Juanita Bay	10
DISCUSSION	12
CONCLUSIONS	14
LITERATURE CITED	32

LIST OF FIGURES

1. The bottom topography of Lake Washington and the location of the sections	19
2. The vertical temperature structure off Fairweather Point, winter of 1962-63	20
3. Temperature profile from Sand Point to Juanita Bay, 11 and 12 January 1963	21
4. Temperature profile from Sand Point to Juanita Bay, 14 and 21 January 1963	22
5. Temperature profile from Sand Point to Juanita Bay, 25 and 27 January 1963	23
6. Temperature profile from Sand Point to Juanita Bay, 29 and 30 January 1963	24
7. Temperature profile from Sand Point to Juanita Bay, 31 January and 1 February 1963	25
8. Temperature profile from Sand Point to Juanita Bay, 18 February and 6 March 1963	26
9. Temperature profile from Sand Point to Juanita Bay, 24 April 1963	27
10. Temperature profile from Kenmore to Fairweather Point, 27 January 1963	28
11. Temperature profile along the axis of the lake from Sand Point to Leschi Park, 21 January 1963	29
12. Daily average air temperature and daily average wind speed at Sand Point	30
13. Heat loss computed from the heat budget and the observed heat loss and computed current in the Sand Point-Juanita Bay section . . .	31



LIST OF TABLES

I. Average daily wind for the warming cycle, 2 February to 24 April 1963	16
II. Meteorological data used in the heat budget calculations . . .	17
III. Terms of the heat budget equation	18

ABSTRACT

The winter convection regime in Lake Washington was investigated, especially the flow along the bottom off the mouths of some of the many shallow bays. The density of fresh water at a given depth, or pressure, is a function of its temperature, so temperature was measured in detail in a portion of the lake during the winter cooling period of 1962-63. The isotherms at the edges of the lake were found to be closely packed and roughly parallel to the sloping bottom. This structure frequently extended to the middle and occasionally across the lake whereas most of the water column in the center of the lake was nearly isothermal. Volume transport was computed from consideration of the amount of heat removed from the deep water of the lake. From the volume transport off Juanita Bay the velocity of the water down the side of the lake was estimated to be 2 cm/sec.

INTRODUCTION

PURPOSE

The purpose of this study is to describe convection in Lake Washington associated with winter cooling under conditions of low wind and large cooling rates. It was necessary to (1) define the vertical and horizontal temperature structure of the lake, (2) compute the heat budget of the lake during the period of winter cooling, (3) compute the vertical transport and associated velocities required for bottom water replacement by convection currents.

NATURE OF THE PROBLEM

The density structure of Lake Washington gives a measure of the potential for flow of the system. Since the density of fresh water at a given depth is a function of temperature and the amount of dissolved or suspended material, measurement of these variables at successive times will give the potential for flow of the system. In addition, it will be possible to define the advective flow in the layers of the lake below the depth of direct surface influence, as all changes of heat at depth are the result of advection (diffusion is considered to be relatively unimportant because the water is nearly isothermal).

PREVIOUS WORK

The term "overturn" was introduced by Whipple in 1895 (Birge, 1904) to describe the annual replacement of bottom water in lakes associated with winter cooling. This choice of terminology appears to be unfortunate because it implies that individual water columns become unstable and capsize. Early workers, particularly those working in

shallow lakes in areas where winter cooling is so great that the lakes freeze, tended to discount the importance of convection. Birge (1910) went so far as to say,

"convection currents are far less important agents for distributing heat than are mechanical currents caused by the wind. Indeed, it would be difficult to show that convection currents have any such efficiency in carrying heat as to make them worth serious consideration."

More recently, Mortimer (1955) recognized a problem with the term "overturn" and was careful to state, "'overturn' connotes the fact that bottom layers previously isolated below the thermocline are brought to the surface." Mortimer goes on to say that such an indefinite statement is necessary because so little attention has been given to water movements leading to the destruction of the thermocline.

The limnology of Lake Washington was discussed by Scheffer and Robinson (1939). They found that bottom water replacement takes place over an extended period in the winter, from December to February or March. The temperature in Lake Washington does not go below the temperature of maximum density of fresh water, 4°C , so that there is no winter stable period.

Rattray, Seckel and Barnes (1954) studied the salt balance in the Lake Washington Ship Canal. They repeatedly occupied a station in the deep part of the lake off Madison Park. They found that there was bottom water replacement even in the presence of a density gradient. They showed that with a density increase of $1.3 \times 10^{-4} \text{ g/cm}^3$ from top to bottom, it was still possible to have an "overturn". The energy for the mixing presumably came from the wind. They also considered the effect of river inflow and concluded that 25 percent of the lake volume was flushed each year.



Gould and Budinger (1958) proposed that convection currents were responsible for the W-shaped bottom profile of Lake Washington. They postulated that currents arising in the shallow bays around the edges of the lake were strong enough to erode the foot of the slopes, or at least to prevent deposition of sediments there. This is an alternative mechanism for the replacement of bottom water in the presence of a density gradient. The water need only become very dense locally in the shallow bays; it can then flow under the water in the central portion of the lake, displacing the local water, with its associated density structure, upward into regions where the structure can be altered by wind action and heat exchange across the surface. This process will continue as long as water in the bays is colder than the main body of the lake, which agrees with the observation of Scheffer and Robinson that bottom water replacement occurs over an extended period.

Church (1942) worked on the annual temperature cycle in Lake Michigan. He found that with a density increase of $1.5 \times 10^{-4} \text{ g/cm}^3$, over the depth range encountered in Lake Washington, stability was maintained against a wind of Beaufort force 2. In Lake Michigan, however, the wind might have been the dominant factor in the breakdown of the thermocline. Winter winds in that area were very strong and there were few shallow bays to serve as source areas of cold bottom water.

DESCRIPTION OF LAKE WASHINGTON

Lake Washington is a narrow lake with its long axis in a north-south direction. It is about 1.5 miles wide and 18.5 miles long. Along



much of the length of the lake there is a rise of 2 to 10 m, giving transverse profiles a subdued W-shape (fig. 1). The margin of the lake is indented by many shallow bays. The lake communicates with the salt water in Puget Sound by an 18-mile canal with a lock at the seaward end. A more extensive discussion of the morphology of the lake is given in Gould and Budinger (1958).

MATERIALS AND METHODS

Temperature was measured with a thermistor which formed one leg of a Wheatstone bridge. The bridge output, which was nearly linear with temperature, was fed into a millivolt recorder. The correction to the thermistor output for heating by the bridge current was always less than 0.01°C ; the correction was considered negligible.

In normal operation, the full scale recorder range was 2°C , giving a sensitivity of 0.01°C . The system was calibrated by the Applied Physics Laboratory, University of Washington. The accuracy of the system was checked by field comparisons with reversing thermometers. A bias of 0.13°C was found. All temperature determinations have been corrected for this bias which did not change during the program.

The standard deviation of the difference between temperatures determined by the reversing thermometers and the thermistor was 0.031°C . Part of the variability is associated with the limits of accuracy of the reversing thermometer and part with the inaccuracy of the thermistor. The standard deviation of the averaged determinations by a pair of reversing thermometers has been given as 0.012°C (Fofonoff, 1963). Since the variance of a sum of independent random variables equals the



sum of the variances, the standard deviation of the thermistor approximates 0.028° C. The precision of the thermistor (as defined by twice the standard deviation) is therefore about 0.05° C, which is about one-half the precision of the reversing thermometers.

Chlorinity was determined by the Volhard method. The carbonates and sulfides in the lake water interfere with the Mohr titration which is usually used on sea water.

Positions were determined either by horizontal sextant angles or by magnetic bearings from a pelorus on the flying bridge.

INVESTIGATION

THE TEMPERATURE STRUCTURE

The vertical temperature structure at a station on the east side of Lake Washington off Fairweather Point was monitored during the winter of 1962-63 (fig. 2). Cooling continued from the first observation on 26 December until 31 January. During this time, no unstable water columns were observed, with the possible exception of the last few meters on 29 and 30 January. A temperature increase in the bottom layers existed in previous years (Rattray, Seckel and Barnes, 1954) when dissolved salt stabilized the water column.

If the water columns observed on 29 and 30 January were stabilized by dissolved salt, there would have to be a chlorinity difference of 0.007 per mille in the bottom 3 m. The temperature inversion was too close to the bottom to permit sampling there. The inversion also could have been caused by a turbidity current moving out into the deep water. The column would remain stable as the sediment settled and the inversion disappeared. Measurements with a hydrophotometer in shallow water indicated that there was suspended material near the bottom.

The lake off Fairweather Point was isothermal on 26 December and 10 January. On 14 January the surface layer had cooled, but there was a large temperature decrease in the last 7 to 8 m. The decrease was present on 21 January, while the thermocline was much shallower than it was earlier. Surface warming began on 1 February, but deep water continued to cool. Cooling was probably caused by the arrival of cold water which was in transit when surface warming began. By 6 March,



warming had taken place at all levels and thermal stratification began.

Stratification was more pronounced by 24 April and the temperature had increased throughout the water column, suggesting an appreciable movement of water from the surface to depth during the initial warming. The process of replacement of bottom water during warming is different from replacement during cooling. The source of energy for replacement during warming is the wind. The spring storms cause some mixing to the bottom. In 1963, winds stronger than any during cooling period occurred on 3 and 26 February, 15, 18, 28, 29, 30 March, 15 and 22 April (table I).

Thirteen sections were made from Sand Point to Juanita Bay (fig. 3 to 9). They covered the two major cold periods in January, and the return of stratification with warming. In all sections during the cooling period, there was a large tilt to the isotherms near Juanita Bay. The tilted isotherms and the low temperatures in the bay was an indication of flow out of the bay along the bottom.

The cold water often found in the deep on the Sand Point side of the section did not appear to have originated in Juanita Bay, as the isotherms were not continuous from the mouth of the bay. That water was too cold to have come from Juanita Bay. Water from that source would have been warmer because of mixing currents. The surface water near Sand Point was never as cold as the water in the deep paths of the section. The coldest water was in the thalweg, the line of greatest depth along the axis of the lake. The most probable origin of that water was in the northern portion of the lake.

A section from Kenmore to Fairweather Point was prepared to trace the origin of the cold water in the thalweg (fig. 10). The section is a

composite of sections from Kenmore to Sand Point on 27 January and from Sand Point to Fairweather Point on 25 January. The temperatures in the portion of the earlier section were adjusted to the levels prevailing 27 January.

There was a marked similarity between the temperature structures in the north end of the lake and the Sand Point-Juanita Bay sections. This was expected because the north end of the lake has extensive shallow areas for the formation of very dense water. The cold water at the foot of the slope in the Kenmore region presumably was not isolated from the cold water in shallower depths, as continuity was maintained along the thalweg.

A section from Sand Point to the deepest part of the lake, off Leschi Park, was taken on 21 January (fig. 11). The cold water in the central region corresponded in position to both Fairweather Bay on the east and to Union Bay on the west and probably represents the cold water flowing into the deepest part of the lake from each side.

HEAT BUDGET

Knowledge of the heat budget made it possible to compare the observed heat loss in a portion of the lake with the computed heat loss expected from meteorological conditions. If the observed heat loss and the computed heat loss agreed, then all of the heat was removed through the surface. If the observed and computed heat loss disagreed, then there must have been exchange of water and heat across the lateral boundaries of that part of the lake.

The terms in the heat budget equation were incoming radiation (Q_s), reflected radiation (Q_r), back radiation (Q_b), evaporation (Q_e), and conduction of sensible heat (Q_h). The incoming radiation was measured with an Eppley pyrhelimeter on top of a three-story building (Johnson Hall on the University of Washington campus) about 1.5 miles from the lake. The remaining terms were calculated from expressions given by T. Laevastu (1960), modified slightly for fresh water.

$$Q_r = 0.15 Q_s - (0.01 Q_s)^2$$

$$Q_e = (0.26 + 0.077 V) (e_w - e_a) (0.1 L)$$

$$Q_b = 20.65 (14.38 - 0.09 T_w - 0.046 r) (1 - 0.0765 C)$$

$$Q_h = 36 (0.26 + 0.077 V) (T_w - T_a)$$

Where all of the Q's are in g cal/cm²/day:

T_w is the temperature of the water surface in °C,

T_a is the temperature of the air in °C,

r is the relative humidity in percent,

C is the cloud cover in tenths,

V is the wind speed in m/sec,

e_w is the saturated vapor pressure at the temperature of the surface in mb,

e_a is the vapor pressure of the air above the water surface in mb,

L is the latent heat of vaporization in cal/gm.

Laevastu uses 39, instead of 36, as the coefficient in his equation for the transfer of sensible heat. The value comes from the choice of the constant in the Bowen ratio. Limnologists have used a slightly different value of this constant, resulting in a smaller coefficient in the equation of sensible heat transfer (Anderson, 1954).



The meteorological data used to make the heat budget calculations were obtained from the weather facility at Sand Point Naval Air Station (table II). The anemometer was 10 m above the lake level, the wet and dry bulb thermometers were 8 m above lake level. The two major cooling periods in January 1963, with daily average temperatures less than 0° C, had an associated increase in wind speed (fig. 12). The heat budget was computed from 10 January to 1 February (table III).

DOWNSLOPE CURRENT OFF JUANITA BAY

There are two main assumptions in the calculation of downslope current off Juanita Bay. The first is that there is no flow into or out of the Sand Point-Juanita Bay section, so that all of the heat loss must take place at the surface. The second is that the influence of surface processes does not extend below 20 m. If this assumption is violated, the computed current will be too high. For the purposes of this calculation, the Sand Point to Juanita Bay section was divided into three parts.



The volume transport was determined by the amount of water at the average temperature of Juanita Bay, region II, which would have to mix with the water in region I to produce the observed heat loss there. The formula used was:

$$V = \frac{\Delta \text{Heat}}{(T_I - T_{II}) \rho C_p \Delta t}$$

where V is the volume transport in cm³/sec;



Δ Heat is the change in heat of the water in region I from one time to the next,

T_I is the average temperature of region I,

T_{II} is the average temperature of region II,

ρ and C_p are density and specific heat (assumed to be 1),

Δt is the time in seconds between sections.

The current velocity was found by dividing the volume transport by the area through which the current flowed. The vertical temperature structure in the slope region off Juanita Bay showed that the flow varied in thickness from 1 to 5 m. Since the thickness of the flow was usually closer to 5 m, that value was used in the calculation. This choice gave a conservative estimate of the computed current velocity.



DISCUSSION

Although dissolved salt contributed to the density structure of the lake in the past (Rattray, Seckel and Barnes, 1954), 20 chlorinity determinations showed that any contribution to the density structure was small. The maximum chlorinity increase from the surface to the bottom at four deep stations was 0.003. This would cause a change in the density equivalent to a temperature change of 0.1°C . One station off Leschi Park on 18 February had a maximum chlorinity difference in the water column of 0.009 per mille. The chlorinity was never greater than 0.011 per mille; the average was 0.004 per mille.

The observed heat loss in the Sand Point-Juanita Bay section was compared to the calculated heat budget (fig. 13). The observed heat loss in the section was about 20 percent smaller than the computed heat loss. There are three possible reasons for this discrepancy:

- (1) the heat budget equations become less accurate as shorter periods are considered,
- (2) the change in heat content from one day to another is a small difference between two large numbers,
- (3) there may be a loss of cold water through the lateral boundaries of the section at depth.

The third alternative seems to be the most probable. Anderson (1954) said that the accuracy of the heat budget for periods greater than 7 days is ± 5 percent. Allowing for the greater accuracy of meteorological data, the heat budget for a period of 22 days should be accurate to at least ± 10 percent. The accuracy of the observed heat change also increases as longer periods are considered.



It is proposed that the computed current be increased by 20 percent to compensate for the water that flows out of the sides of the section at depth. The average flow velocity would then be about 2 cm/sec.

Assuming an average heat loss of $300 \text{ cal/cm}^2/\text{day}$, the top 5 m of the lake would cool at a rate of 0.6° C/day . A flow of 2 cm/sec would cause complete replacement of the water in Juanita Bay in 1.5 to 2 days. In that time a parcel of water in the bay would cool 0.9° C to 1.2° C . Such cooling corresponds well with the observed temperature decrease in Juanita Bay.



CONCLUSIONS

The bottom water in Lake Washington is formed in the many shallow bays that surround the lake. The bays temporarily confine the water as it cools, allowing it to become denser than the water in the main body of the lake. The cold, dense water then flows out of the bay and down the slope, mixing with and displacing the original deep water, resulting in a bottom layer of nearly uniform temperature.

The shape of a cross section determines in part whether that section has an observed heat loss which is greater or less than the surface heat loss computed from the heat budget. Water from sections with extensive shallow areas will flow out of those sections into the deep parts of adjacent sections that do not have large shallow areas. Continuity requires a return flow at some other depth, probably near the surface. Because of this removal of cold water from the section in which it was formed, sections with large shallow areas will not become as cold as expected when heat loss is computed from meteorological conditions. Similarly, sections without extensive shallow areas will become colder than expected, because of the lateral influx of cold water and loss of warmer water.

Correcting for the escape of cold water through the sides of the Juanita Bay section, the estimate of the current velocity was 2 cm/sec.

Future studies should include cross sections off both shallow embayed areas and steep-sided areas off straight shores. They should also include routine sections to give a better picture of movements along all axes. This however, would require more than one vessel and



was not considered within the scope of the present exploratory work. In areas where the flow is concentrated, as off the mouth of a bay, a dye tracer could be used to follow water parcels and get additional information for estimating water velocities.



TABLE I

AVERAGE DAILY WIND FOR THE WARMING CYCLE, 2 FEBRUARY TO 24 APRIL 1963

<u>Date</u>	<u>Wind</u> <u>m/sec</u>	<u>Date</u>	<u>Wind</u> <u>m/sec</u>	<u>Date</u>	<u>Wind</u> <u>m/sec</u>	<u>Date</u>	<u>Wind</u> <u>m/sec</u>
2 Feb.	2.3	23 Feb.	1.5	16 Mar.	1.6	5 Apr.	2.3
3	5.6	24	0.9	17	2.6	6	3.5
4	4.3	25	2.3	18	5.3	7	1.4
5	1.4	26	5.9	19	3.7	8	2.1
6	2.4	27	1.4	20	1.3	9	1.6
7	1.7	28	3.9	21	3.3	10	2.0
8	1.2	1 Mar.	3.8	22	3.4	11	3.0
9	2.8	2	2.3	23	2.0	12	2.1
10	2.7	3	1.5	24	1.8	13	2.2
11	1.8	4	1.0	25	1.3	14	3.2
12	2.5	5	2.0	26	1.3	15	6.0
13	1.8	6	1.9	27	1.4	16	2.5
14	0.8	7	2.2	28	6.2	17	1.6
15	0.8	8	1.6	29	5.4	18	3.3
16	0.9	9	1.8	30	5.6	19	2.5
17	2.2	10	1.8	31	3.7	20	1.9
18	0.5	11	3.6	1 Apr.	1.9	21	2.4
19	2.4	12	1.3	2	0.7	22	5.1
20	0.6	13	3.1	3	2.5	23	4.2
21	1.0	14	4.2	4	3.3	24	2.5
22	1.3	15	5.0				



TABLE II

METEOROLOGICAL DATA USED IN THE HEAT BUDGET CALCULATIONS

Date	Water Temp. °C	Air Temp. °C	Dew Point °C	Wind Speed m/sec	Cloud Cover tenths
10 Jan.	8.30	-3.0	-14.5	4.8	0
11	8.10	-6.2	-18.2	2.8	0
12	7.94	-4.3	-12.4	1.3	4
13	7.86	-0.6	- 5.1	1.5	10
14	7.78	2.8	2.0	1.2	10
15	7.73	5.8	5.6	1.3	10
16	7.68	4.8	3.9	1.0	10
17	7.64	4.4	3.5	1.8	10
18	7.59	3.1	- 4.7	3.1	3
19	7.54	0.0	- 5.6	0.7	6
20	7.49	1.5	- 3.1	1.3	6
21	7.45	0.8	- 0.5	0.8	8
22	7.41	2.9	1.7	1.5	6
23	7.37	2.3	- 1.4	1.6	8
24	7.33	2.0	0.4	1.0	10
25	7.29	3.3	0.7	2.0	5
26	7.21	0.6	- 3.2	1.5	7
27	7.14	-0.6	- 3.4	1.1	7
28	7.02	-0.1	- 7.7	4.1	5
29	6.90	-0.9	-17.2	2.8	1
30	6.80	-1.4	- 8.7	2.6	9
31	6.74	0.8	0.1	2.1	10
1 Feb.	6.75	3.0	2.3	1.4	8

TABLE III
TERMS OF THE HEAT BUDGET EQUATION
Cal/cm²/day

<u>Date</u>	<u>Q_s</u>	<u>Q_r</u>	<u>Q_b</u>	<u>Q_e</u>	<u>Q_h</u>	<u>Net Out</u>	<u>Observed Heat Loss</u>
10 Jan.	161	22	231	332	257	681	
11	164	22	224	261	246	589	440
12	146	20	160	179	160	373	198
13	30	5	50	145	115	285	198
14	26	4	45	73	63	159	115
15	20	3	44	22	25	74	115
16	50	7	45	38	35	75	115
17	20	3	46	61	46	146	115
18	176	23	177	183	81	288	115
19	107	15	119	119	86	232	115
20	144	20	116	116	78	186	115
21	44	6	76	83	76	197	143
22	70	10	106	76	60	182	143
23	170	23	82	109	72	177	143
24	32	5	46	80	65	164	143
25	142	19	126	92	59	154	244
26	131	18	98	117	88	190	244
27	120	17	99	118	133	247	260
28	181	24	141	221	148	353	260
29	215	28	234	224	132	403	379
30	57	8	71	179	136	337	124
31	33	5	46	92	89	199	70
1 Feb.	80	11	75	57	51	114	



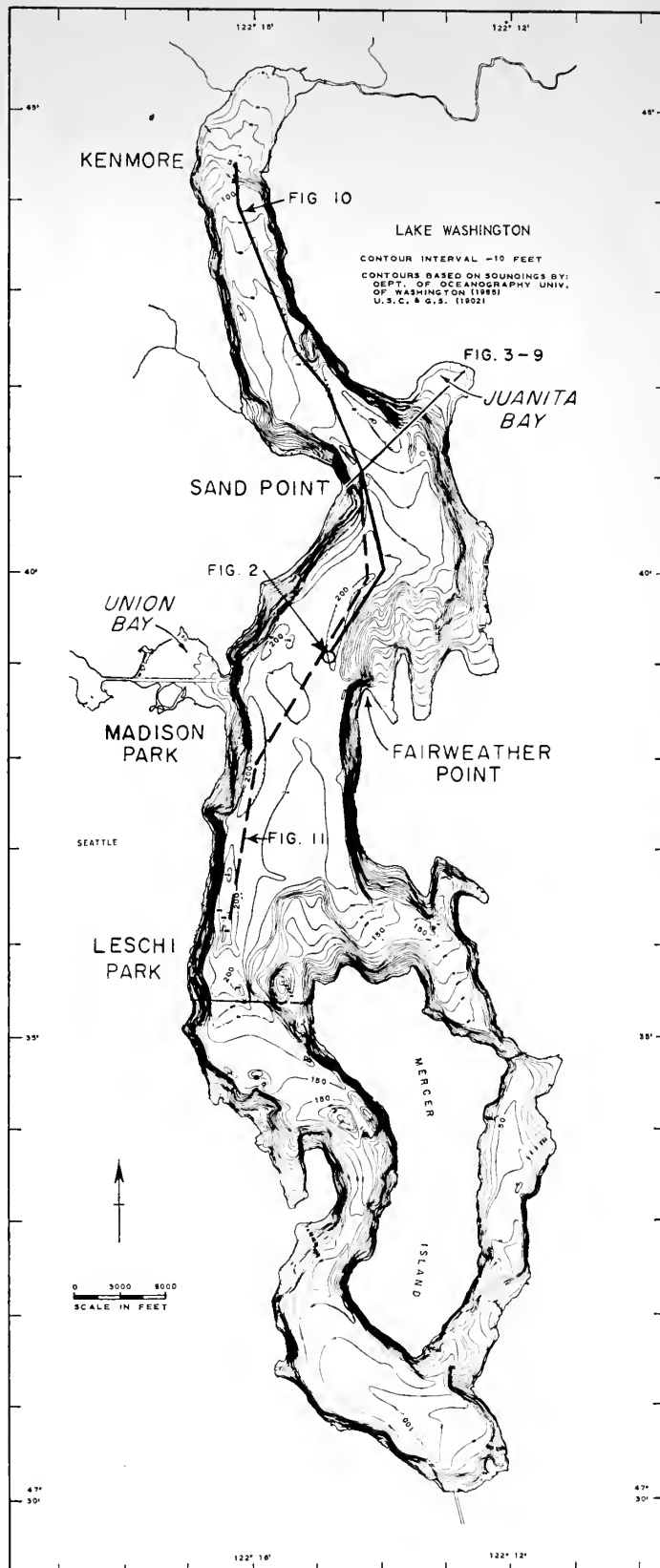


FIGURE 1. The bottom topography of Lake Washington and the location of the various sections.



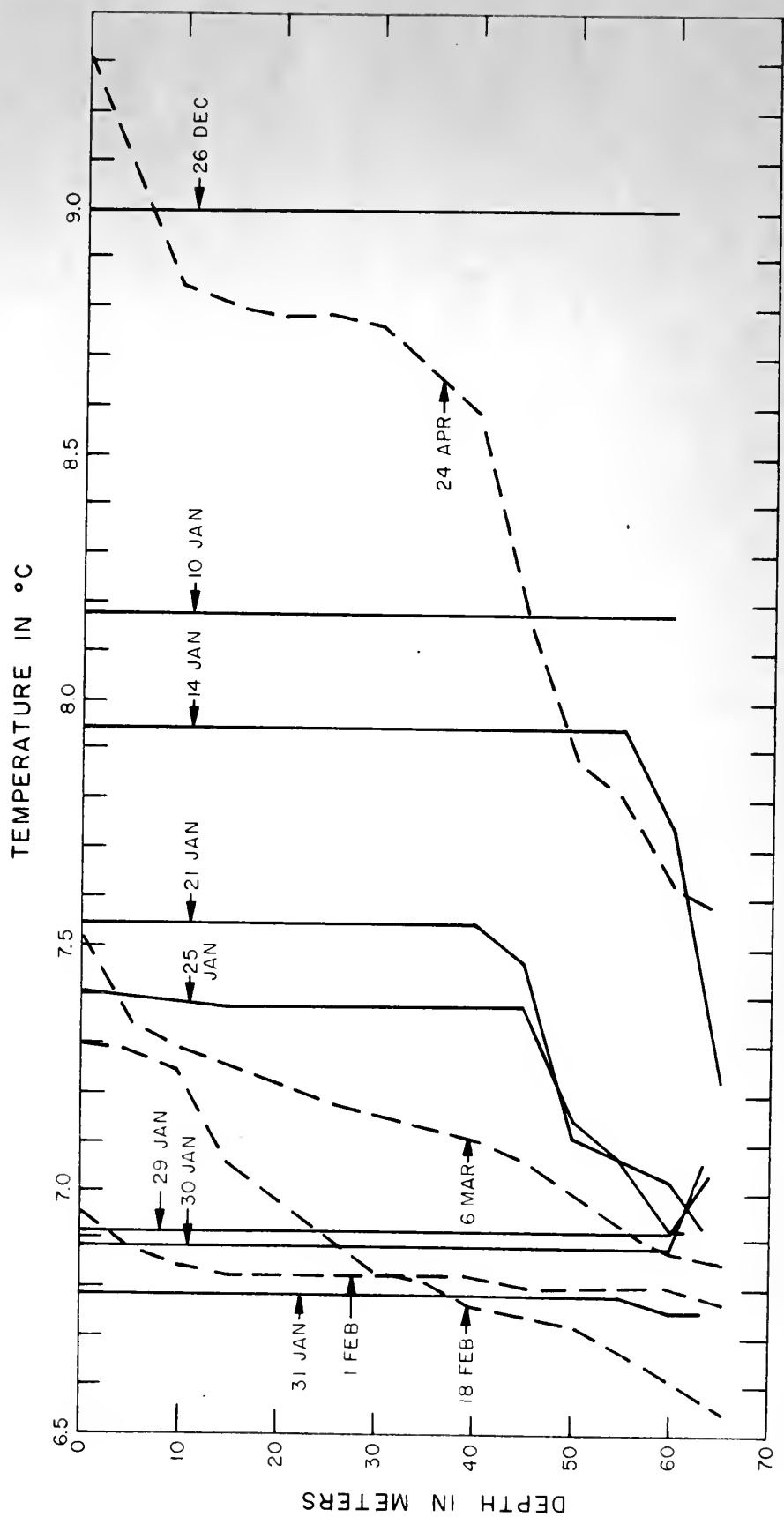
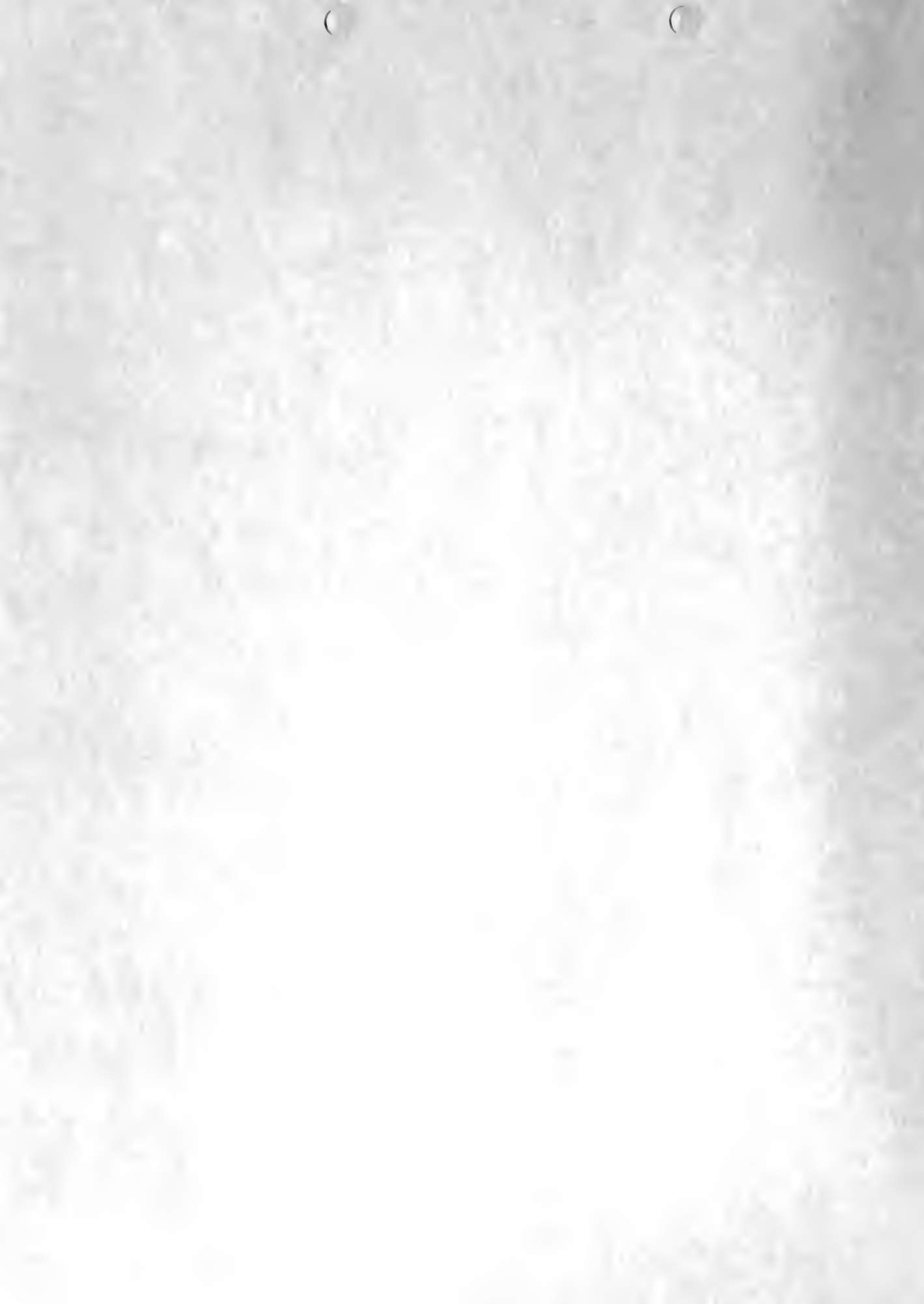


FIGURE 2. The vertical temperature structure off Fairweather Point at various times during the winter of 1962-63.



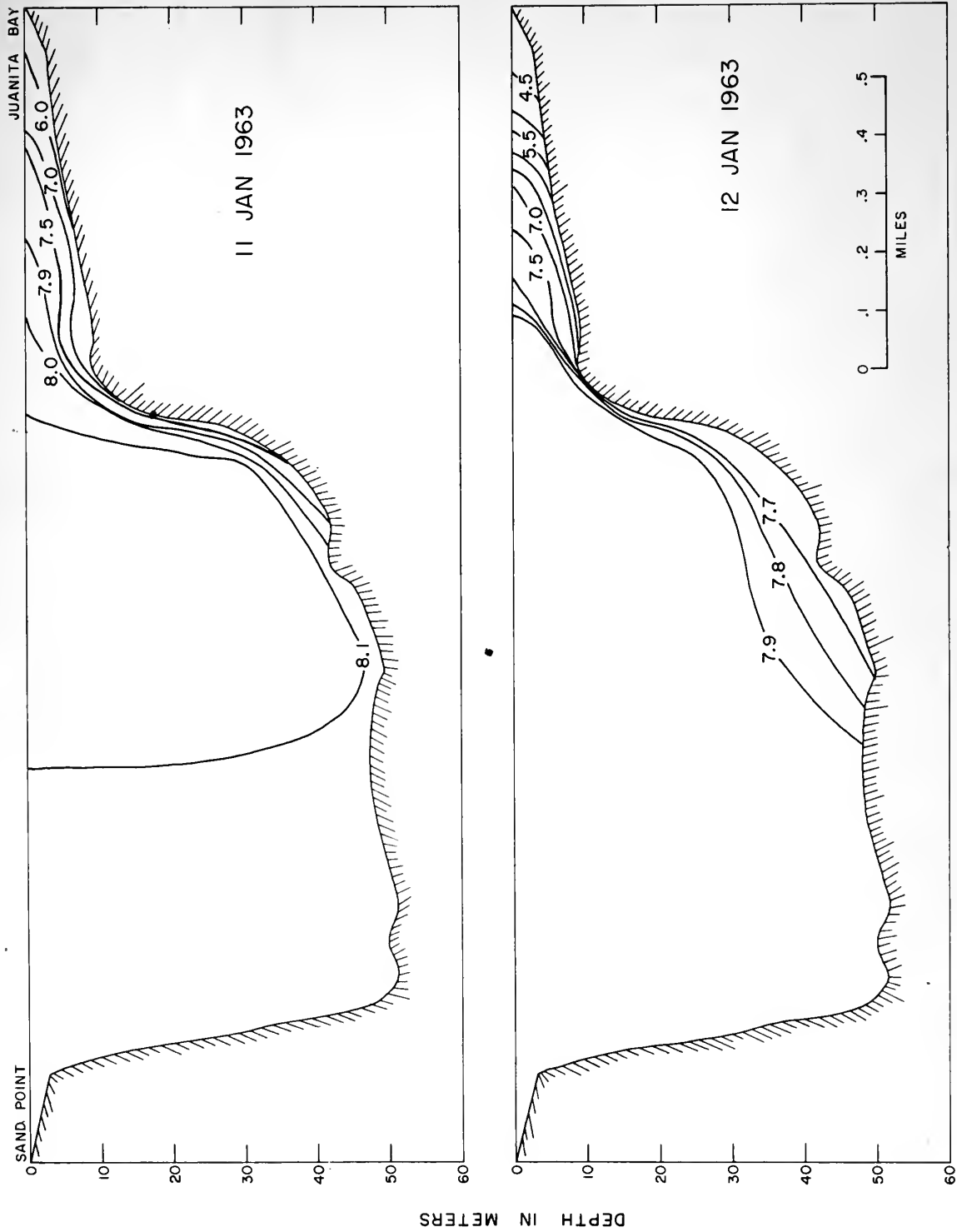


FIGURE 3. Temperature profile from Sand Point to Juanita Bay for 11 and 12 January 1963



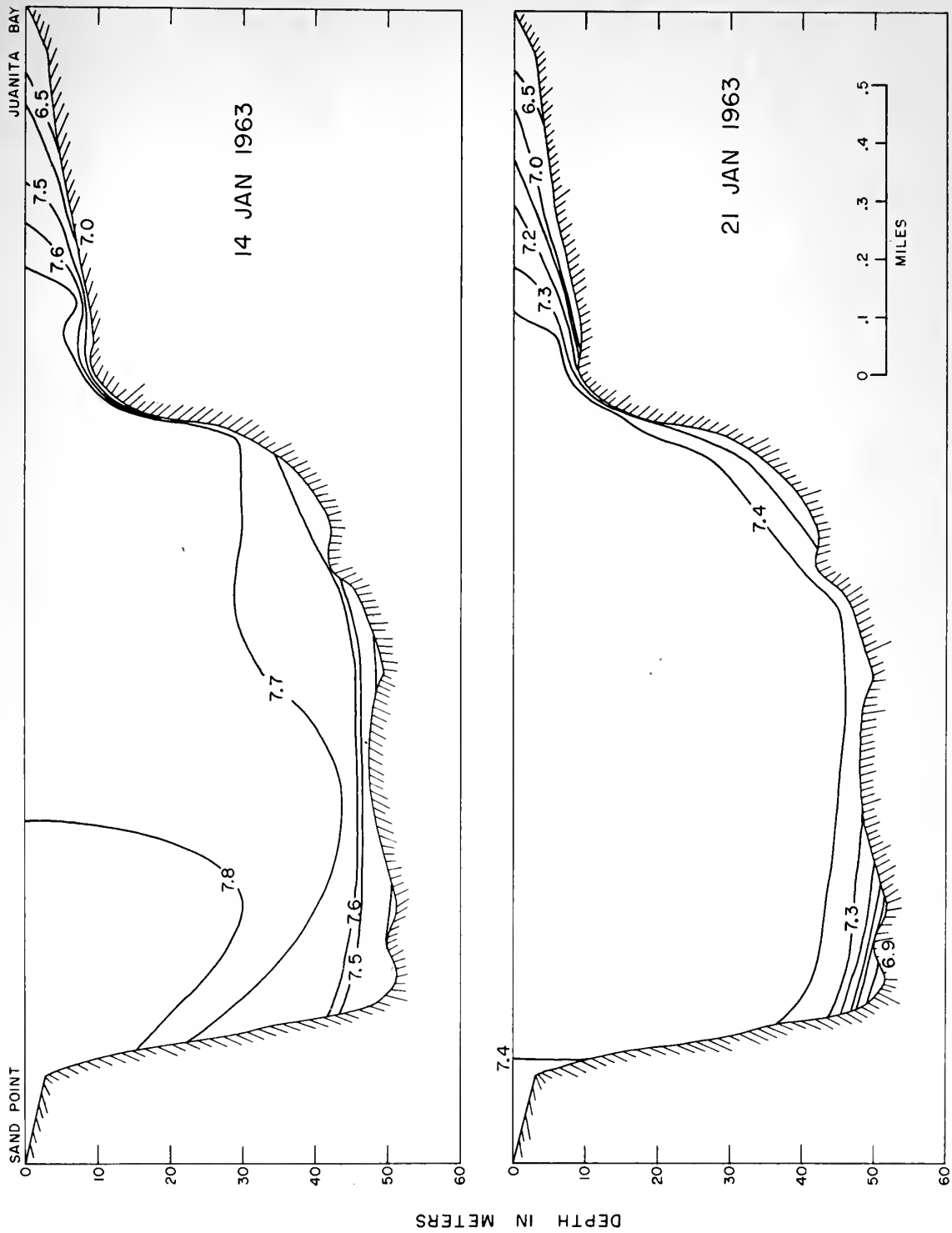
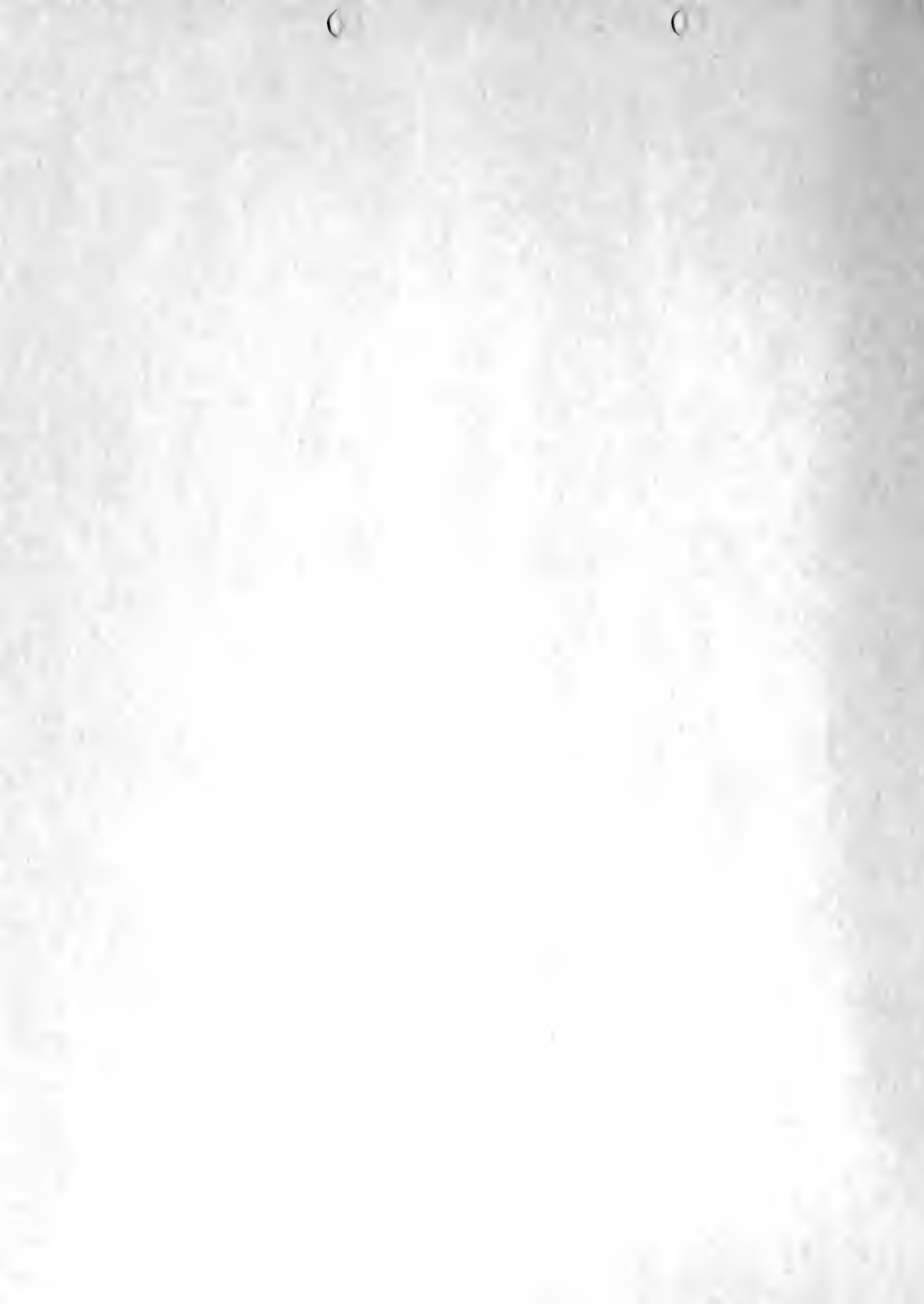


FIGURE 4. Temperature profile from Sand Point to Juanita Bay for 14 and 21 January 1963



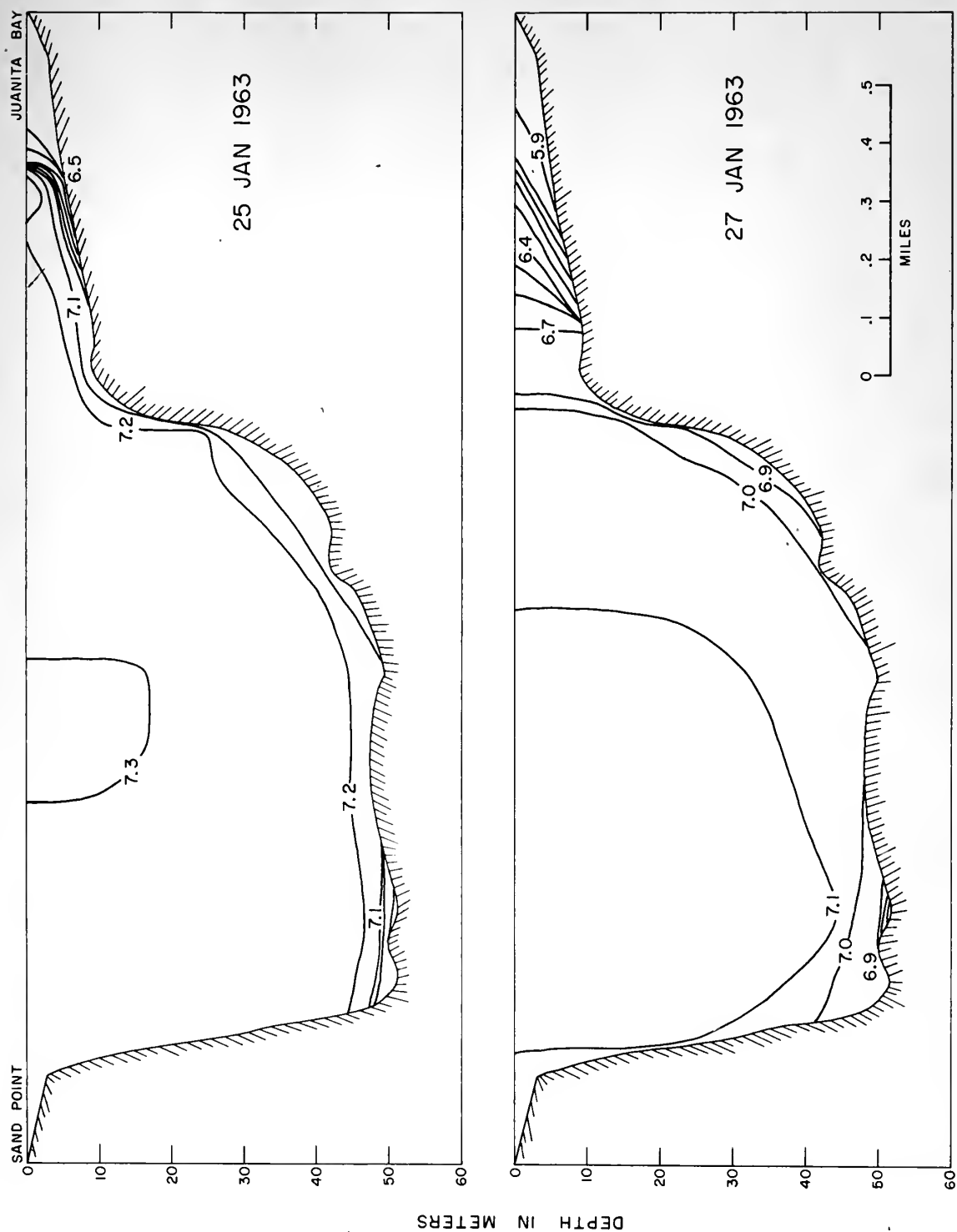


FIGURE 5. Temperature profile from Sand Point to Juanita Bay for 25 and 27 January 1963



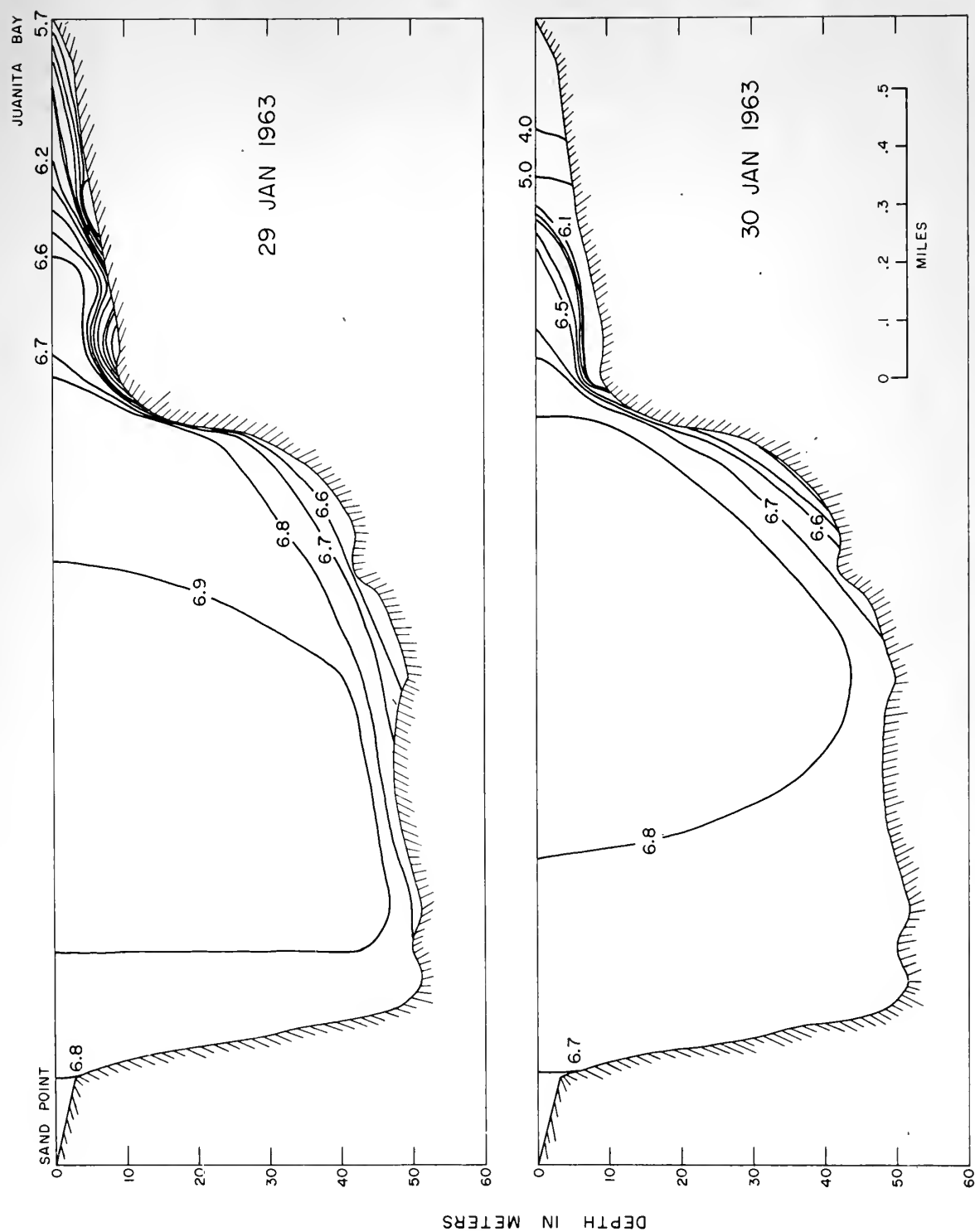
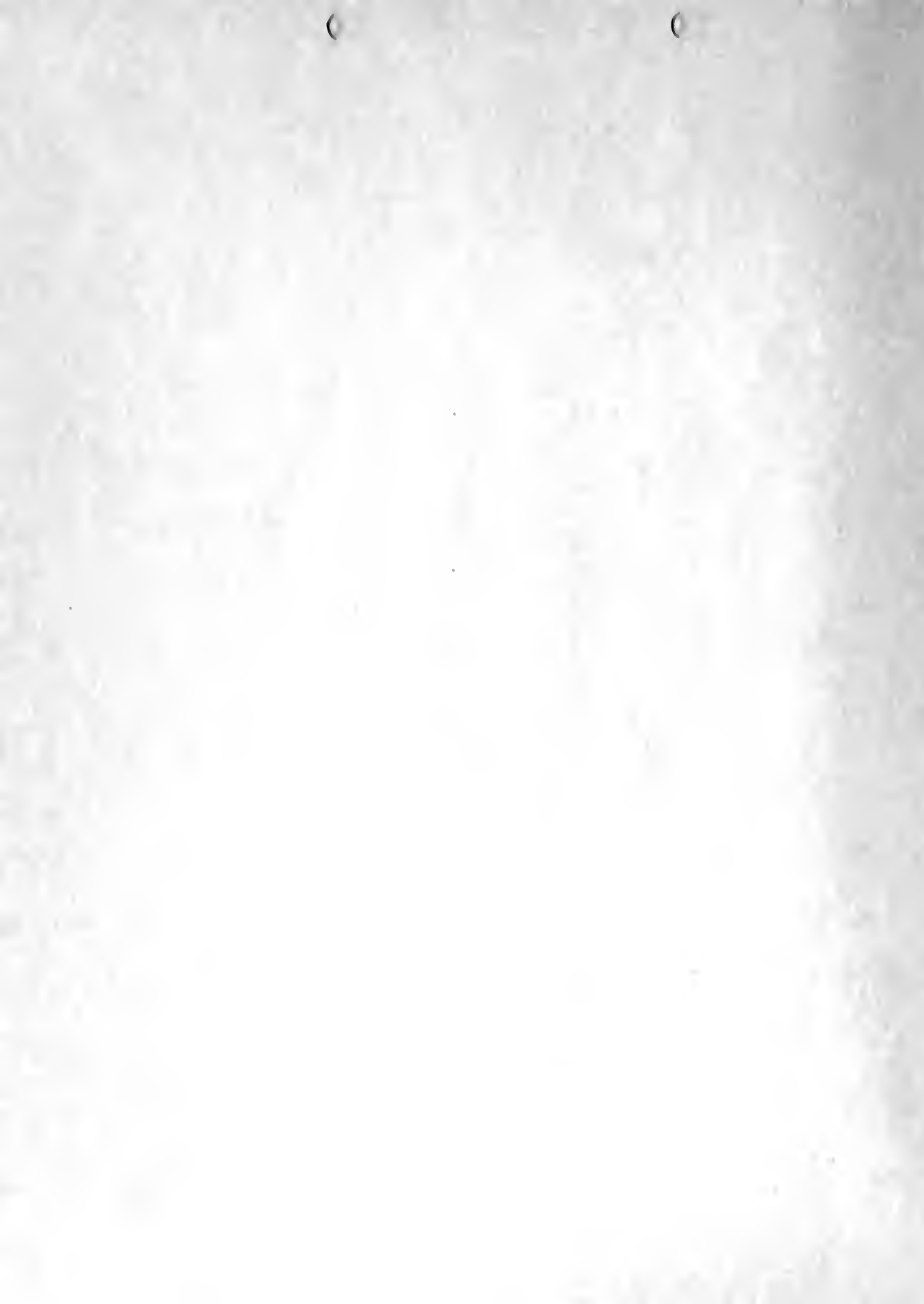


FIGURE 6. Temperature profile from Sand Point to Juanita Bay for 29 and 30 January 1963



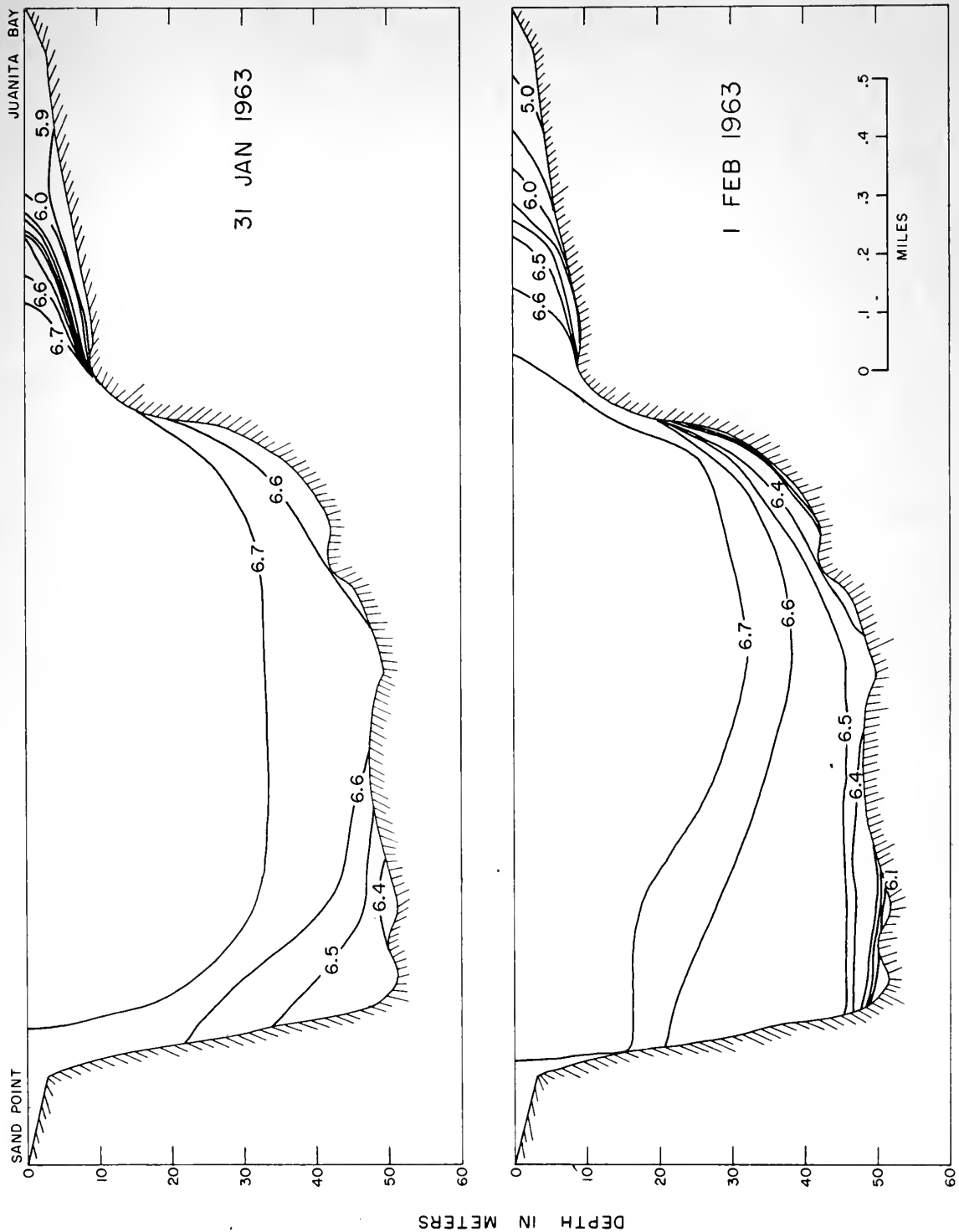


FIGURE 7. Temperature profile from Sand Point to Juanita Bay for 31 January and 1 February 1963



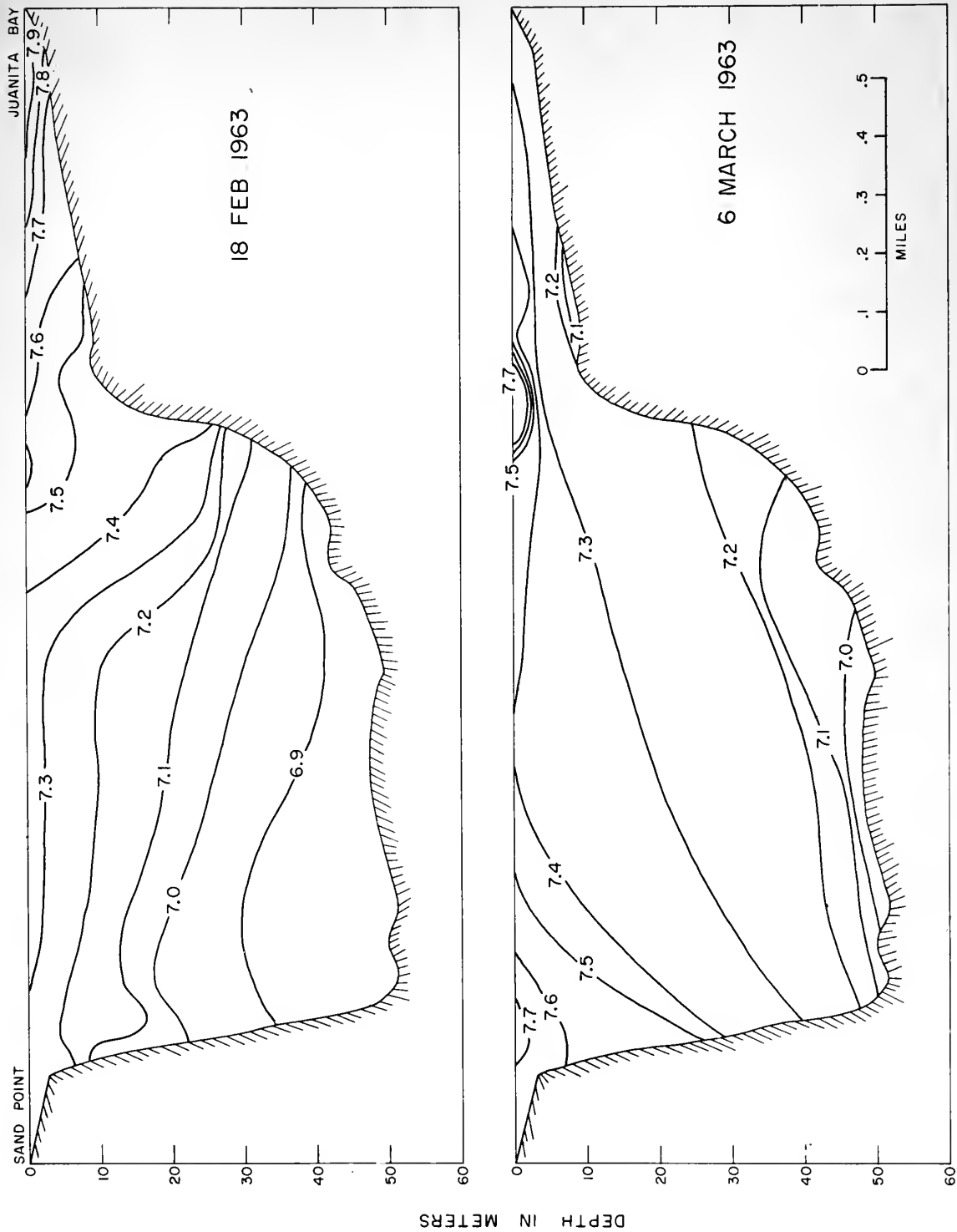


FIGURE 8. Temperature profile from Sand Point to Juanita Bay for 18 February and 6 March 1963



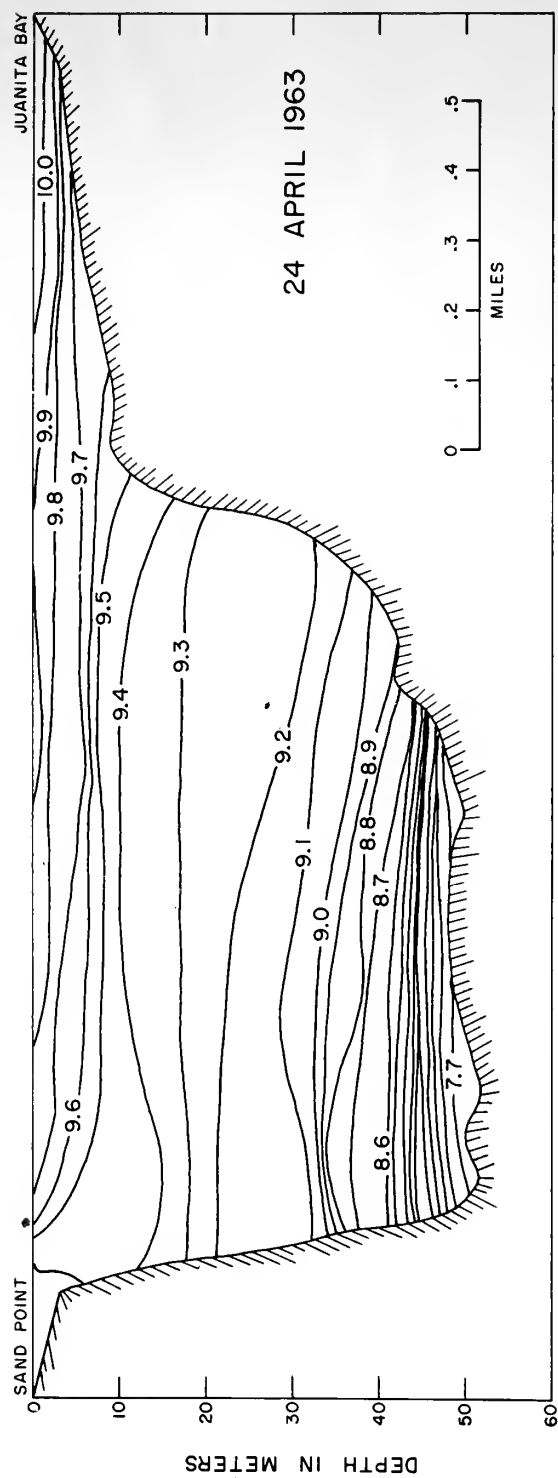
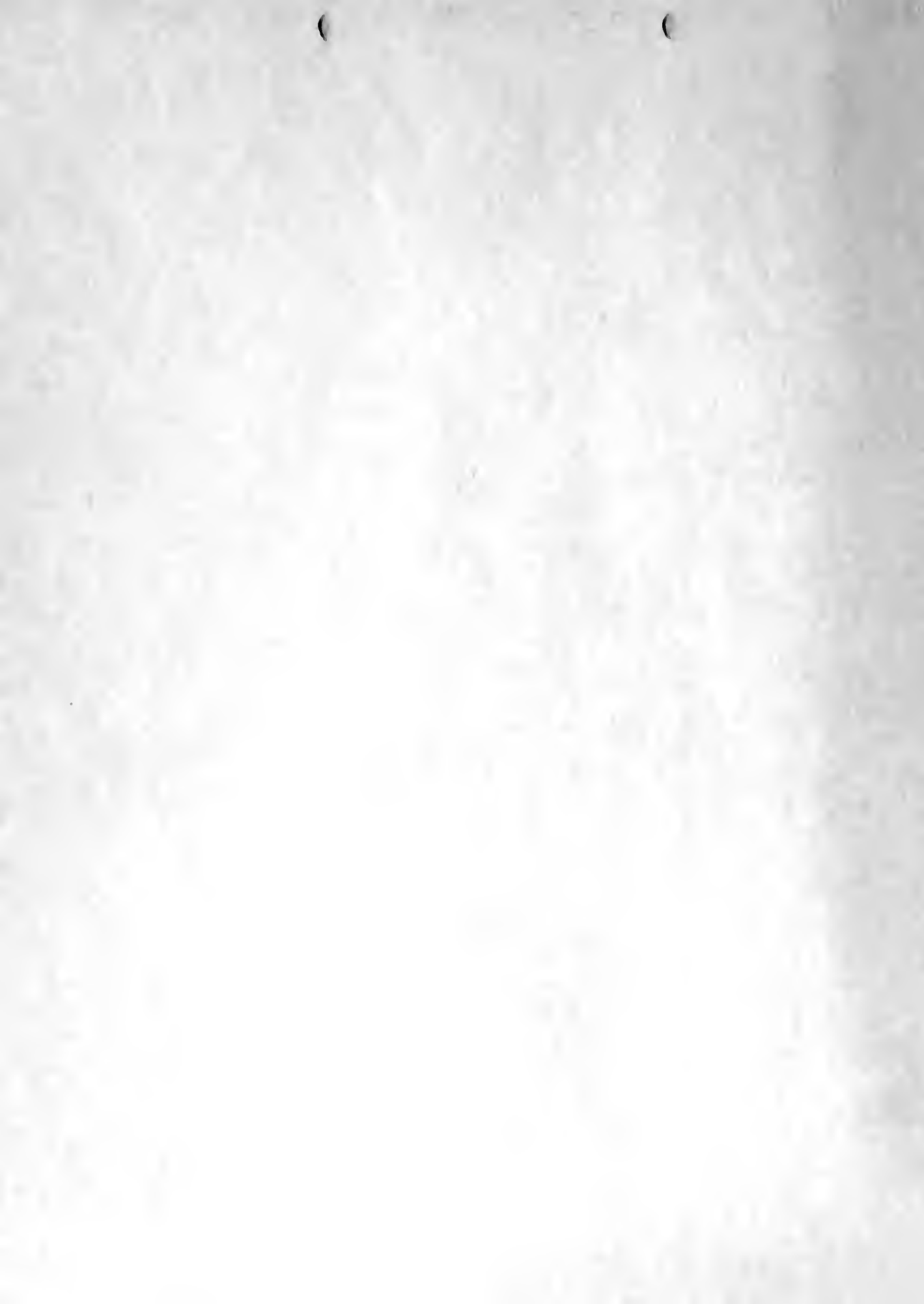


FIGURE 9. Temperature profile from Sand Point to Juanita Bay for 24 April 1963



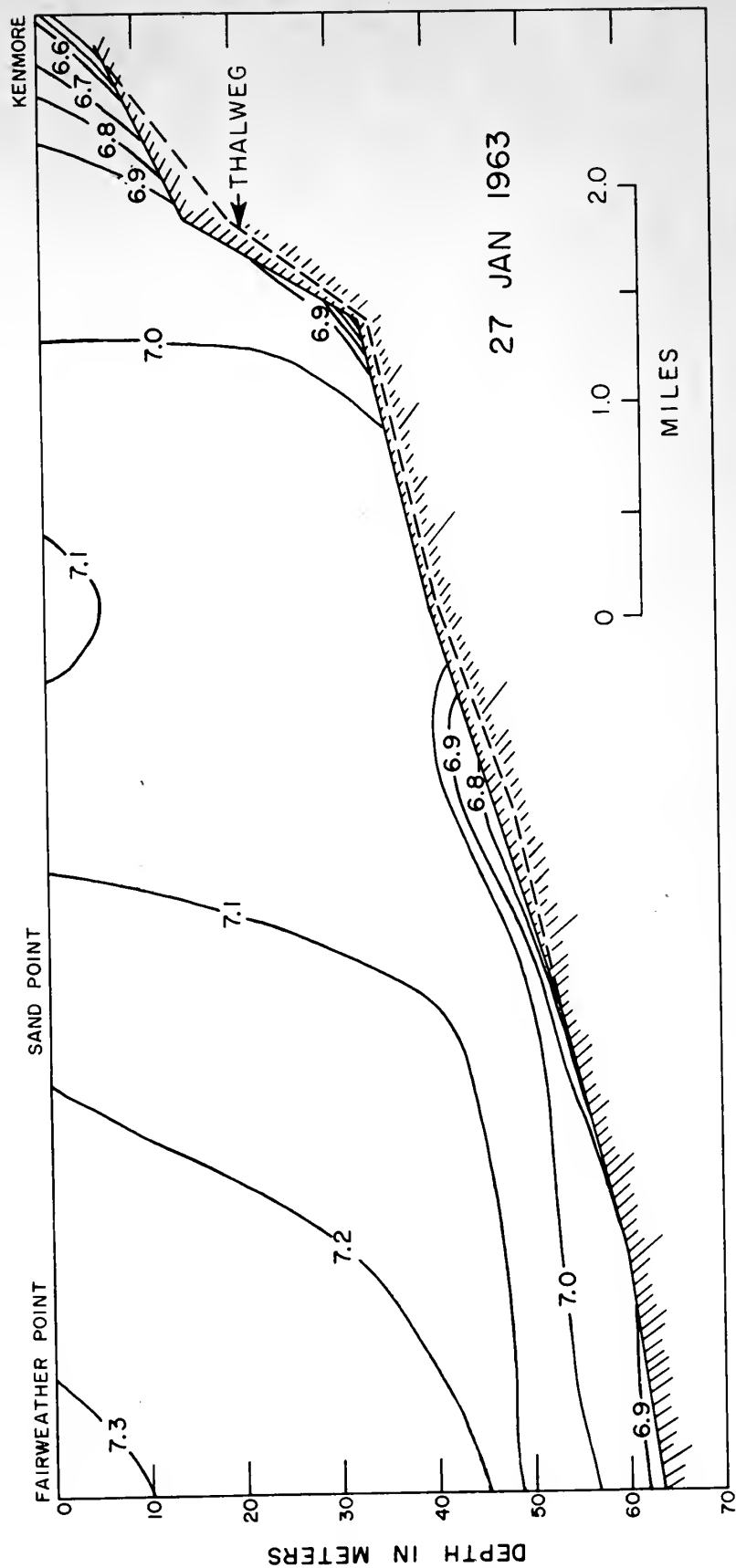


FIGURE 10. Temperature profile from Kenmore to Fairweather Point on 27 January 1963. The thalweg is shown as a dashed line.



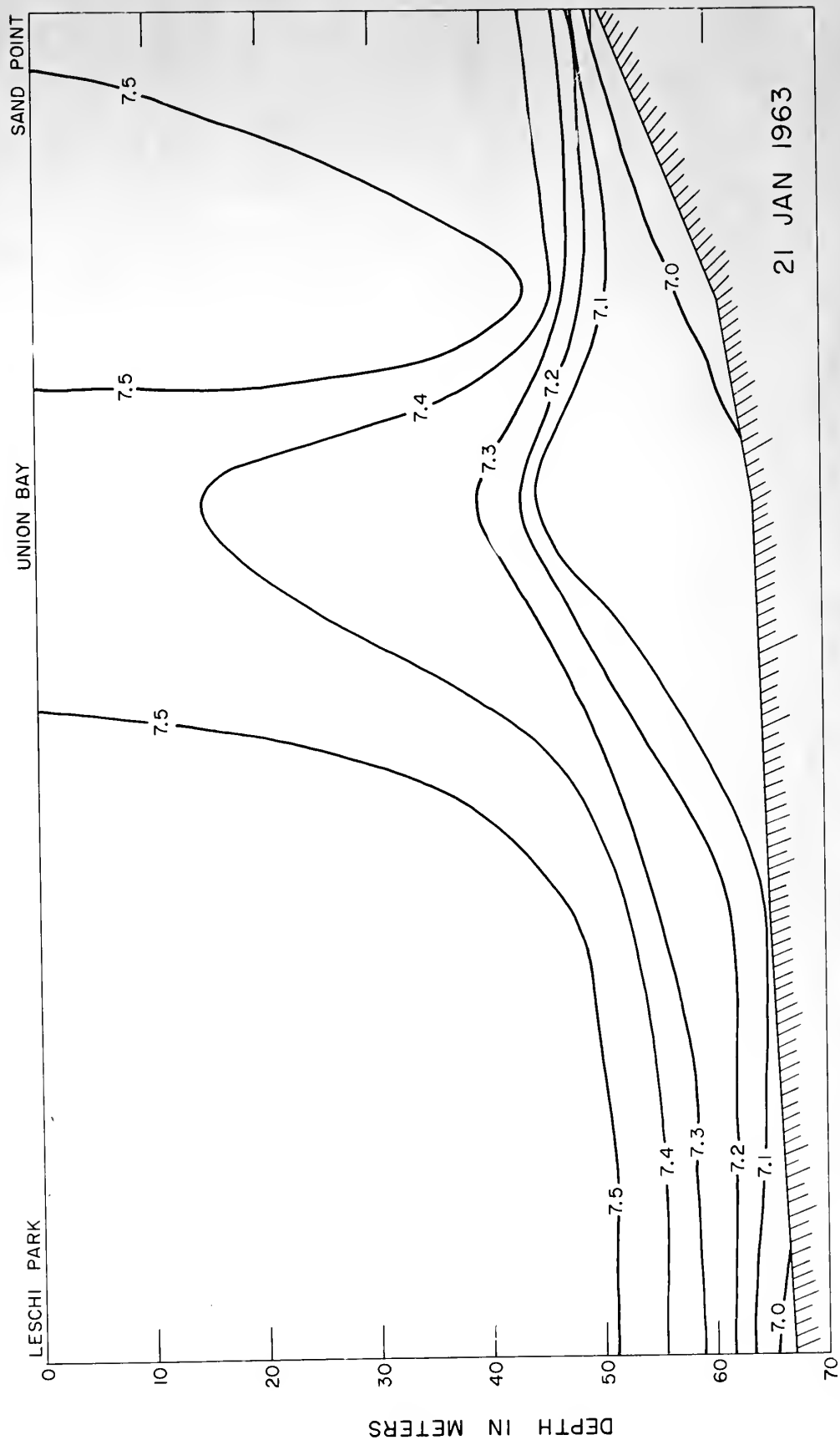


FIGURE 11. Temperature profile along the axis of the lake from Sand Point to Leschi Park on 21 January 1963



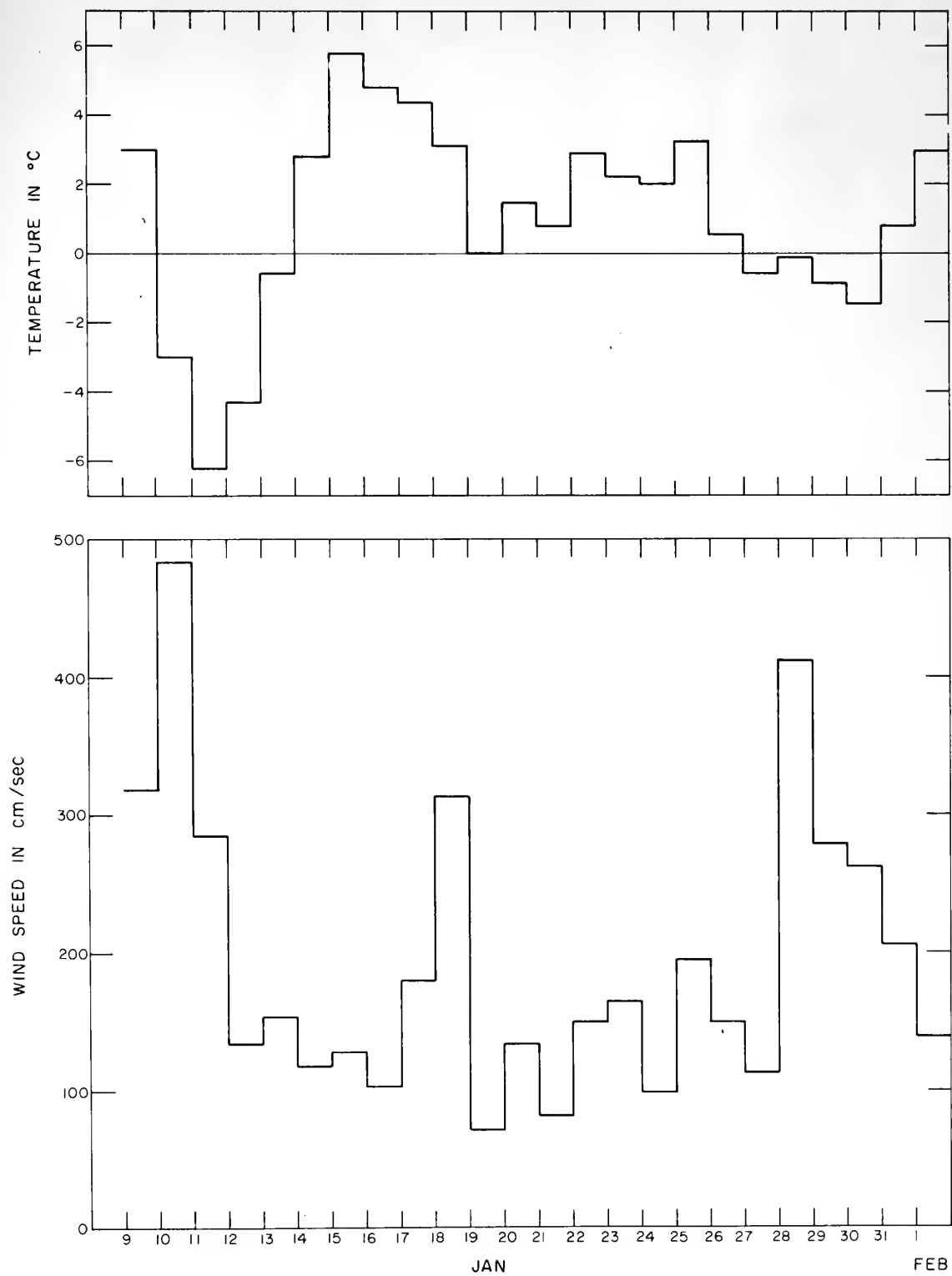


FIGURE 12. Top: Daily average air temperature at Sand Point
Bottom: Daily average wind speed at Sand Point.



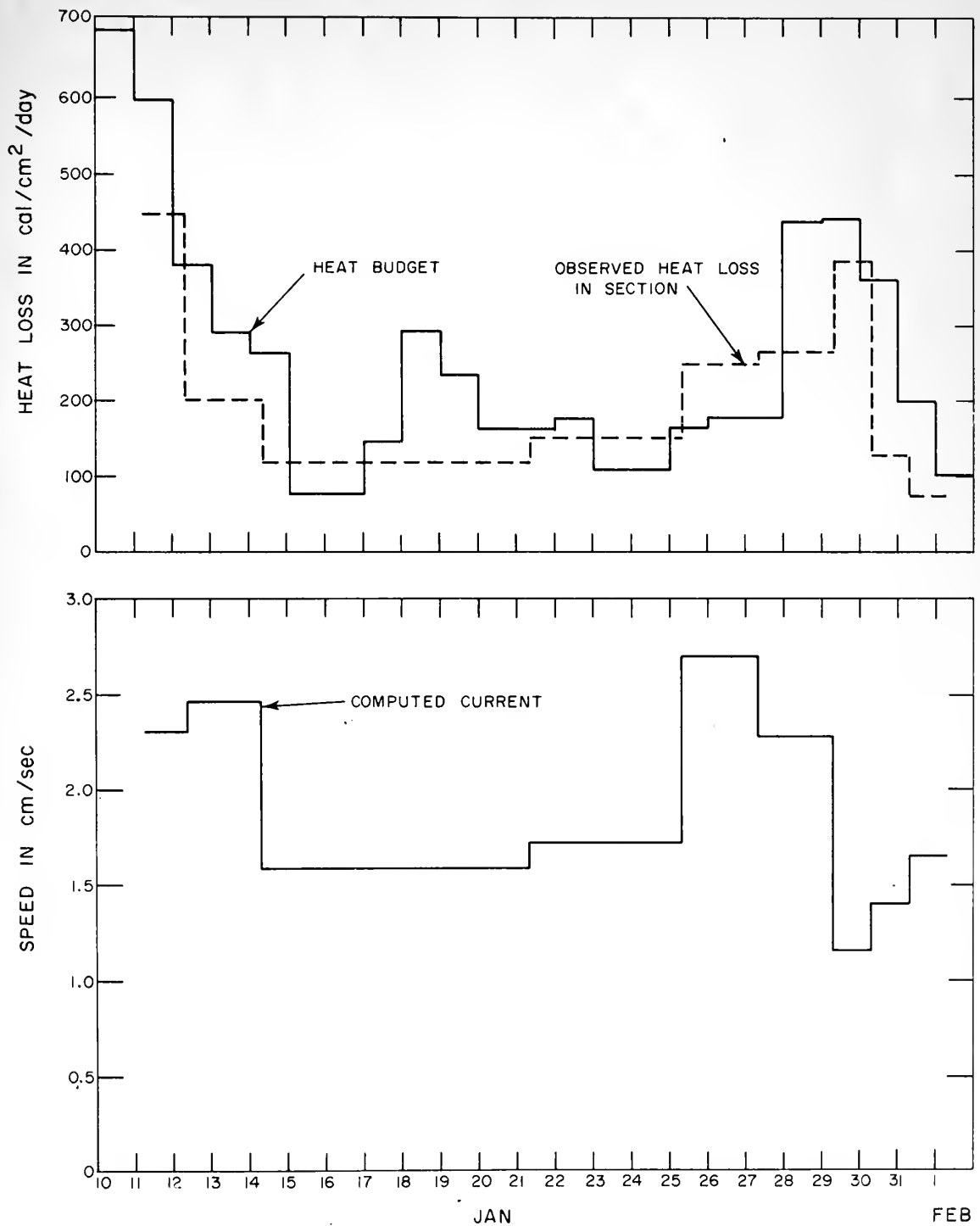


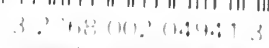
FIGURE 13 Top: Heat loss computed from the heat budget and the observed heat loss in the Sand Point - Juanita Bay section.
Bottom: Computed current in the Sand Point - Juanita Bay section.



LITERATURE CITED

- Anderson, E. R. 1954. 'Energy Budget Studies' in 'Water-Loss Investigations: Vol. 1 - Lake Hefner Studies Tech. Rep.' U. S. Geol. Surv. Prof. Paper, No. 269, pp. 71-119.
- Birge, E. A. 1904. The Thermocline and Its Biological Significance. Trans. Amer. Microscop. Soc., Vol. 25, pp. 5-33.
- Birge, E. A. 1910. An Unregarded Factor in Lake Temperatures. Trans. Wisc. Acad. Sci. Arts Lett., Vol. 16, pp. 989-1004.
- Church, P. E. 1942. The Annual Temperature Cycle in Lake Michigan. Univ. Chicago Inst. Metrol. Misc. Rep. No. 4, 50 pp.
- Fofonoff, N. P. 1963. Precision of Oceanographic Data for Sound Speed Calculations. J. Acoust. Soc. Am., Vol. 35, No. 6, pp. 830-36.
- Gould, Howard R. and Thomas F. Budinger. 1958. Control of Sedimentation and Bottom Configuration by Convection Currents, Lake Washington, Washington. J. Marine Res., Vol. 17, pp. 183-98.
- Laevastu, T. 1960. Factors Affecting the Temperature of the Surface Layer of the Sea. Soc. Sci. Fennica Commentations Phys. Math., Vol. 25, No. 1, 136 pp.
- Mortimer, C. H. 1955. The Dynamics of the Autumn Overturn in a Lake. Gen. Ass. Int. Geod., Vol. 3, pp. 15-24.
- Rattray, Maurice, Jr., G. R. Seckel and C. A. Barnes. 1954. Salt Budget in the Lake Washington Ship Canal System. J. Marine Res. Vol. 13, No. 3, pp. 263-75.
- Scheffer, V. B. and R. J. Robinson. 1939. A Limnological Study of Lake Washington. Ecol. Monographs, Vol. 9, pp. 95-143.





6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 1040 1041 1042 1